## Title

# Objective Metric of Energy Absorbed in Tibial Plateau Fractures Corresponds Well to Clinician Assessment of Fracture Severity



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# Objective metric of energy absorbed in tibial plateau fractures corresponds well to clinician assessment of fracture severity

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## Abstract

**Objectives—**Determine the agreement between subjective assessments of fracture severity and an objective CT-based metric of fracture energy in tibial plateau fractures.

**Methods—**Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered 20 tibial plateau fractures in terms of severity based upon AP and lateral knee radiographs. A CT-based image analysis methodology was used to quantify the fracture energy, and agreement between the surgeons' severity rankings and the fracture energy metric was tested by computing their concordance, a statistical measure that estimates the probability that any two cases would be ranked with the same ordering by two different raters or methods.

**Results—**Concordance between the six orthopaedic surgeons ranged from 82% to 93%, and concordance between surgeon severity rankings and the computed fracture energy ranged from 73% to 78%.

**Conclusions—**There is a high level of agreement between experienced surgeons in their assessments of tibial plateau fracture severity, and a slightly lower agreement between the surgeon assessments and an objective CT-based metric of fracture energy. Taken together, these results suggest that experienced surgeons share a similar understanding of what makes a tibial plateau fracture more or less severe, and an objective CT-based metric of fracture energy captures much but not all of that information. Further research is ongoing to characterize the relationship between surgeon assessments of severity, fracture energy, and the eventual clinical outcomes for patients with fractures of the tibial plateau.

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## Introduction

Fracture severity is commonly assessed by treating orthopedic surgeons to determine prognosis and decide optimal treatment. Outcomes of intra articular fractures are influenced by multiple patient, surgeon, and injury factors. The location of a fracture and its morphology, the quantity of articular surface involvement, and the extent of acute mechanical damage all play a role in defining the severity of a fracture. Fracture “severity” spans a spectrum from low to high. Low-severity fractures have characteristics such as minimal displacement or comminution and are thought to have an excellent prognosis with non-operative treatment. High-severity fractures have characteristics like extensive displacement and comminution and are generally indicated for operative treatment with good to fair prognosis.

These indices, taken together, clearly indicate individual injury specificity. Orthopaedic surgeons formulate treatment strategies based largely on subjective criteria and clinical experience, while accounting for patient-specific demographic and medical conditions. However, subjective methods of fracture assessment such as morphology and classification are often poorly reproducible among orthopaedic surgeons and are inherently unreliable.[1–3] There is a risk that relying upon such methods may lead to poorly conceived treatment algorithms because they are not grounded in objective data.

The greater the amount of energy dissipated in the creation of a fracture (i.e., the fracture energy), the greater the fracture severity. Accurate and reliable measures of the fracture energy can provide objective data for orthopaedic surgeons to use in making treatment decisions and predicting prognosis. Previous investigations have demonstrated that objective CT-based measures of fracture energy in tibial pilon fractures correlate with (1) surgeon assessment of injury severity and (2) two-year radiographic and functional outcomes.[4,5] In this work, we explored whether this technique of objective fracture energy measurement could also be used to stratify the severity of tibial plateau fractures in a manner that would agree with expert opinions of fracture severity. Specifically, we hypothesized that an objective CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity.

## Materials and Methods

A fellowship-trained orthopaedic trauma surgeon (TOM) purposefully selected 20 cases from a series of 50 consecutive tibial plateau fractures to represent a full spectrum of fracture severity and to avoid having multiple fractures cluster around a common level of severity. Fracture classifications included OTA 41-B3 and 41-C3, reflecting the use of CT in assigning classifications and a heavy emphasis on articular surface involvement and depression.[6] Patients sustaining the fractures ranged in age from 18 to 70-years-old. There were 12 males and 8 females. Our Institutional Review Board approved use of the patient data. See Table, Supplemental Digital Content 1 for a summary of demographic information.

Six fellowship-trained orthopaedic trauma surgeons from four separate institutions independently rank-ordered the fractures in order of severity based upon the appearance of the fractures on AP and lateral knee radiographs. The only instructions given to the raters were to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, the amount and direction of displacement, percentage of articular surface involved, and whatever other features they felt were important based on their clinical experience. Raters were blinded to independently obtained CT-derived data and patient information.

A previously validated CT-based image analysis approach was used to quantify the fracture energy based upon measurement of the fracture-liberated surface area and accounting for bone density. This method has been shown to be accurate in calculating fracture energy (i.e. the amount of energy dissipated in fracturing the bone)[7,8], but the extent of its clinical utility is still under investigation. Fracture energy is expressed in the units of Joules (J), which are equivalent to Newton-meters or kg-$m^2/s^2$. Software, custom-written in MATLAB, was used to identify all fracture fragments working from standard-of-care axial CT image data. The surfaces of the fragments were then classified as subchondral, cortical, or inter-fragmentary based upon their associated CT intensities and their local geometric character (surface roughness, curvatures, etc). The surface classifications were subsequently manually confirmed to be accurate, or modified as needed, by an experienced analyst (Figure 1). The interfragmentary surface areas of all of the fracture fragments were summed to provide a single aggregate measure of the fracture-liberated surface area. Bone density values were obtained based on previously established relationships with Hounsfield intensity of CT scan pixels[9], and the fracture-liberated surface areas were scaled accordingly to reflect the influence of bone density upon the fracture properties. Fracture energy was calculated from a previously validated formula based upon the fracture mechanics principle that energy is directly proportional to fracture liberated surface area scaled by bone density in a brittle solid.[7,8]

We tested our hypothesis by comparing the surgeon rank orderings of fracture severity in this series of tibial plateau fractures with CT-based measurements of fracture energy. The agreement between fracture severity assessments among the surgeons, and between each of the surgeons and the fracture energy metric, was tested by computing their concordance. The injury severity rankings of two cases were deemed concordant if the case with the higher ranking of injury severity by one rater/metric also had the higher ranking by a second. The concordance was calculated as the number of concordant pairs divided by the total number of possible pairings. This sample-based statistical measure was used to estimate the probability that two cases would be ranked with the same ordering. Random assignment of fracture severity by two reviewers would be expected to result in a concordance of 0.5 because any case pairing would have a 50% chance of being concordant.

## Results

Fracture energies ranged from 5.46 J to 36.73 J (see Table, Supplemental Digital Content 1). There was a high level of agreement between the six experienced surgeons in their assessments of tibial plateau fracture severity, with concordances ranging from 82% to 89%, with a mean of 85% (Figure 2). The concordance between surgeon severity rankings and the fracture energy severity ranking were slightly less high, ranging from 73% to 78%, with a mean of 74%.

Case 19 (as ranked by rater 1) is an example of excellent agreement between orthopaedic surgeons and fracture energy. Severity rankings ranged from 17–20 with a fracture energy of 24.5J (Figure 3). Substantial articular surface comminution and normal bone density led to a high fracture energy calculation. This feature as well as substantial fracture displacement, knee dislocation, and bicondylar fracture morphology all contributed to high ranking by the orthopaedic surgeons. Despite the good overall agreement observed between surgeon assessments of fracture severity and the fracture energy metric, there were some notable exceptions. Case 18 demonstrated substantial discrepancy between the objective fracture energy metric and all six subjective ratings (Figure 4). The orthopaedic surgeons all rated this fracture as high in severity, while the fracture energy value was modest (11.9 J). The radiographs demonstrate significant fracture malalignment, which would not be reflected in the fracture energy. In contrast, case 7 was a clear outlier with a much higher fracture energy value (17.9 J) relative to the low severity rank assigned by all six raters (Figure 5). The common "split-depression" (OTA 41-B3) was typically deemed lower severity by all surgeons, but closer inspection of the sagittal CT section demonstrates significant comminution leading to a higher fracture energy measurement.

## Discussion

The purpose of this study was to determine whether a CT-based fracture energy metric could provide an objective, quantifiable measure of tibial plateau fracture severity by comparing it to the current gold standard, subjective expert surgeon opinion. We found a high level of agreement (85%) regarding fracture severity among the six orthopaedic trauma subspecialists. The level of agreement between surgeon assessments of fracture severity and fracture energy was 74%, suggesting that fracture energy has clinical relevance. These results demonstrate that fracture energy reasonably mirrors expert opinion regarding the relative fracture severity over a full spectrum of tibial plateau fractures. This builds on the findings of previous investigations of tibial pilon fractures and shows that fracture energy may be used as a measure of injury severity in other intra articular fractures as well.

The two major benefits of using fracture energy rather than clinician assessment are its ability to physically quantify severity and its objective nature. Quantifying fracture energy allows for distribution of fracture severity over continuous scales ranging from the entire spectrum of injury severity to subtle differences not appreciated by clinical assessment. In contrast, current classification schemes place fractures into one of several categories and often do not distinguish between substantially different injuries. Objectivity in calculating fracture energy is also valuable because it prevents clinician bias and disagreement resulting from subjective assessments and ensures reproducibility of calculations through rigorous algorithms.

The Schatzker classification and OTA classification are two common subjective methods that categorize tibial plateau fractures and convey information about fracture severity. The inter-observer reliability of assigning fractures within these two classifications based upon radiographs ranges from 0.38 to 0.47 and from 0.36 to 0.43 (Kappa statistic), respectively.[1–3,10] When the classifications are based on CT, the reliabilities increase to 0.76 and 0.73, respectively.[10] Although concordance values cannot be directly compared to correlation, our concordance rates of 73 to 78% fracture energy and surgeon ranking suggest a similar or better level of agreement relative to current classification strategies. Although this study does not necessarily support incorporating fracture energy calculations into clinical practice, it demonstrates clinical relevance of fracture energy. Therefore, fracture energy can be used to quantify injury severity as an objective, continuous variable in studies comparing two groups of fractures to determine extent of group similarity. This is superior to common methods of comparing severity between groups using fracture classification.

It may also be that fracture energy predicts outcomes as a function of treatment. Perhaps excellent outcomes can be expected following non-operative treatment of a low-severity fracture (fracture energy of 6 J), while poor outcomes with non-operative treatment (and good outcome with operative treatment) can be expected for a high-severity fracture (fracture energy of 30 J). If that were the case, then measurement of fracture energy would be helpful to determine operative indications as well as predict future patient function.

There are several inherent inaccuracies and discrepancies in CT-based measurements and surgeon observations. First, the fracture energy calculation was based solely on fracture-liberated surface area and bone density. It does not yet account for other fracture features observed by surgeons, such as fracture displacement, malalignment (Figure 4), fracture morphology (e.g. extent of articular surface comminution versus metaphyseal comminution), or the ease of fixing the fracture, all of which may influence outcomes. Decreased bone density also directly reduces objective energy measurements. In contrast, it is possible that surgeons examining radiographs would ascribe a higher severity to an osteopenic fracture based on fracture fixation difficulties often encountered in such injuries. This would lead to higher severity ranking by surgeons compared to lower fracture energy calculations. Another factor leading to higher surgeon ranking of severity relative to fracture energy is that the surface area metric is based on brittle material assumptions[11] and does not account for plastic deformation. Therefore, impacted metaphyseal and articular surface fragments, which often have significant compaction of underlying trabecular bone, may have absorbed higher levels of energy than were measured. This could lead to an artificially lower fracture energy calculation, particularly in fractures with significant articular surface comminution. Finally, a limitation of the study unrelated to the technique for measuring fracture energy is that the orthopaedic surgeons judged fracture severity based solely on plain radiographs, but the fracture energy calculation was based on CT scan data. Therefore, there were likely instances in which certain fracture characteristics not appreciated on radiographs may have led to underestimation of fracture severity by surgeon assessment.

Fracture displacement, undeniably one of the most important clinical assessment criteria, was not included in the fracture energy metric. This was because regression analysis in our prior work[7] identified fracture energy and articular comminution as statistically significant PTOA predictors ($P < 0.01$), but not fragment displacement ($P = 0.35$). Actually, fracture energy and fracture displacement were only loosely linked in that work. This may partly be because injury CT scans are often obtained after the application of a temporary external distractor.

This work is a preliminary interrogation of a novel method to yield objective evidence that may eventually prove useful to guide treatment decisions. However, there are no data yet from our study that correlate fracture energy and clinical outcomes. Surgeon rank-order assessment of fracture severity is a reasonable subjective index but has no objective jurisdiction in predicting outcomes. In this study, we chose to use this subjective measure as there is currently no other standard against which to compare fracture energy. Further investigation is ongoing to determine if quantified relationships between objective fracture energy indices and objective measurements of clinical outcomes can be established.

In conclusion, an objective CT-based measurement of fracture energy demonstrated good concordance with fellowship-trained orthopaedic trauma surgeon subjective assessment of injury severity in tibial plateau fractures, adding to previous work reporting similar findings for tibial pilon fractures. Ongoing investigation will determine the clinical utility of these measurements.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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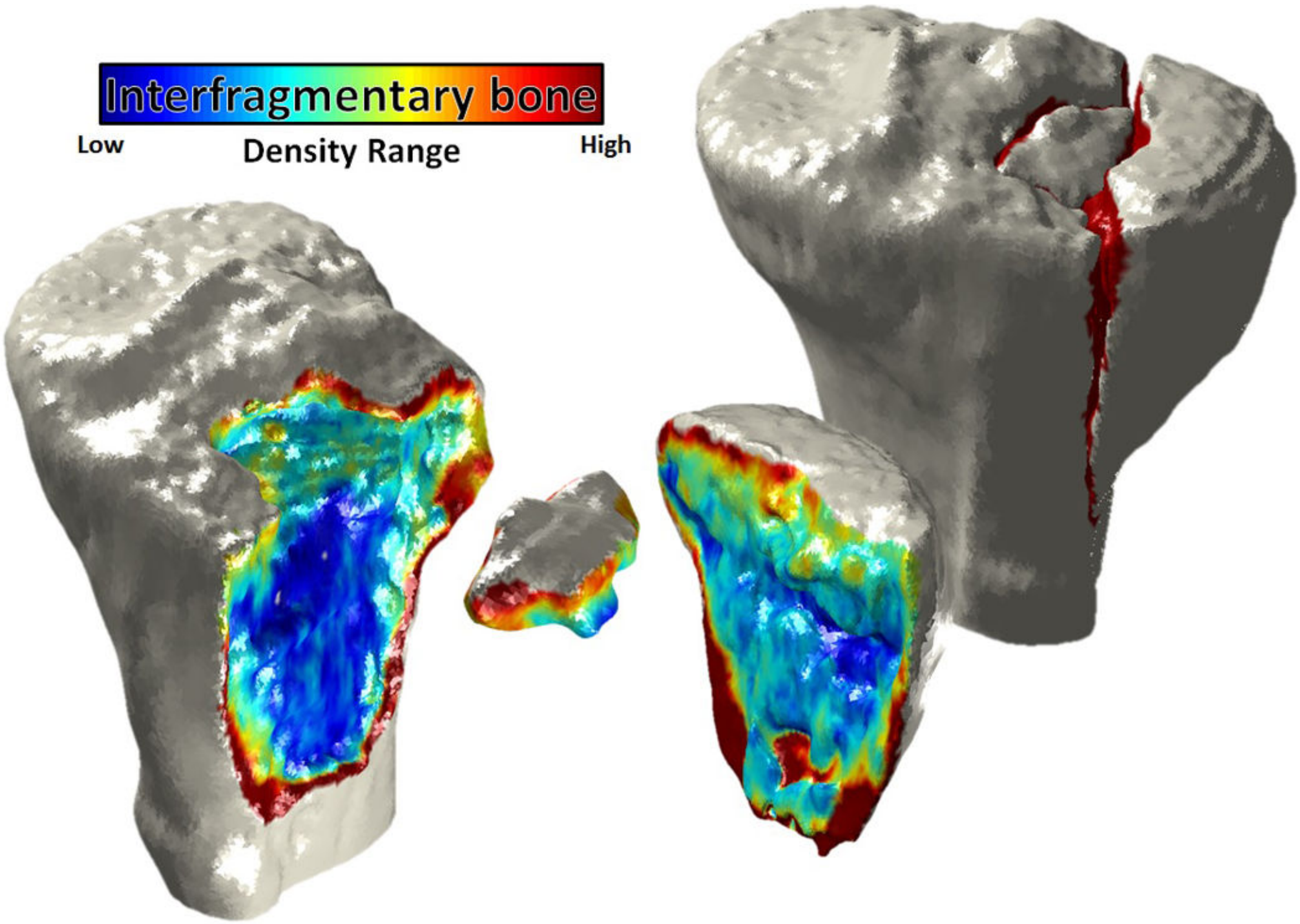


**Figure 1.**

Custom-written software was used to measure the surface area of the fracture-liberated cancellous (interfragmentary) bone surfaces, colored according to their local density in the exploded view to the left. The fracture-liberated surface area and bone densities were both used to calculate fracture energy.

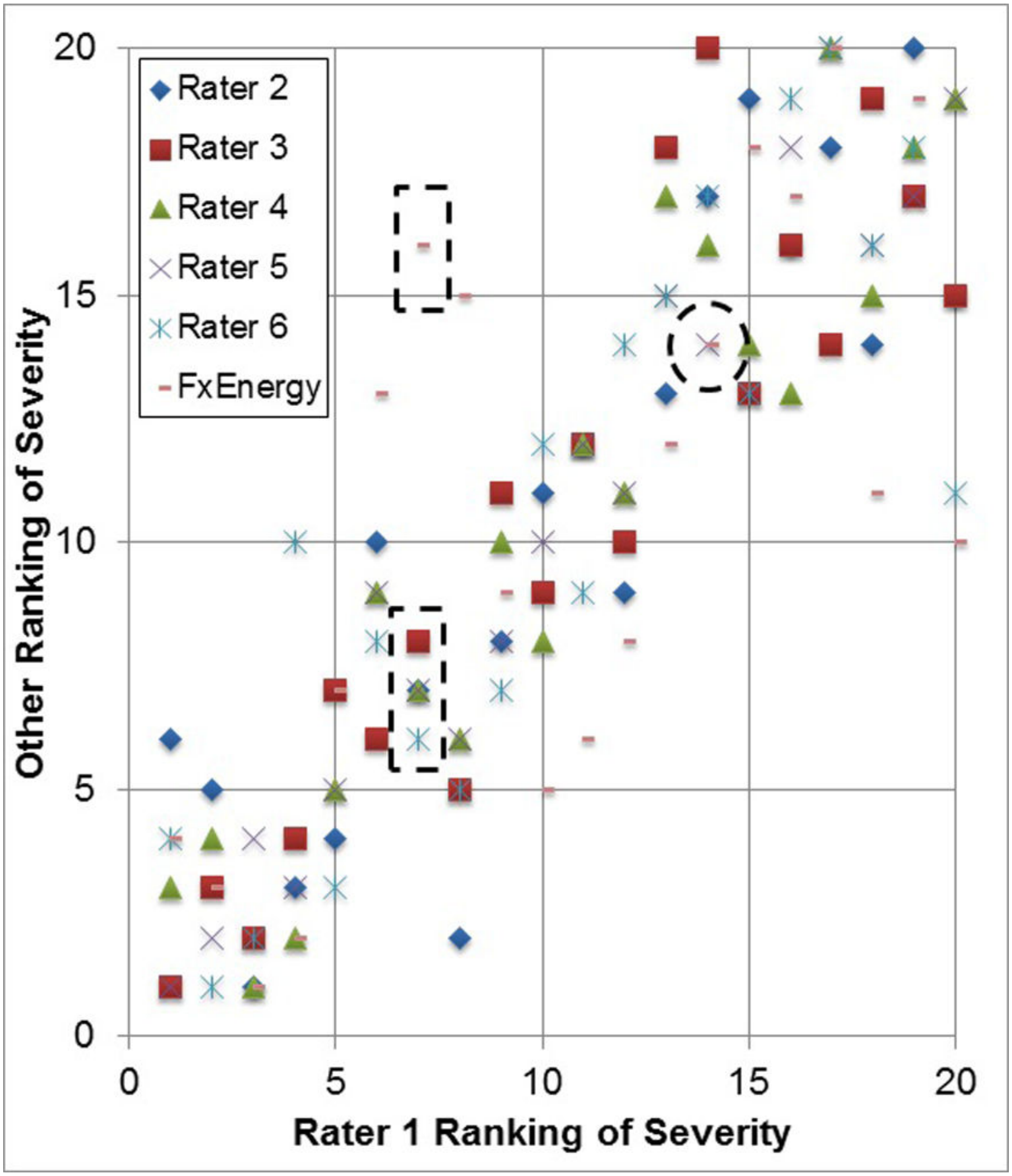


**Figure 2. Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy**

The y-axis represents severity ranking as assigned by raters 2–6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 through 6 at rater-1 injury number 7, but this fracture's rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle).

**Figure 3. Example of high level of agreement between orthopaedic surgeons and fracture energy calculation**

These AP and lateral knee radiographs demonstrate a bicondylar tibial plateau fracture with substantial articular surface comminution and displacement and an associated knee dislocation.

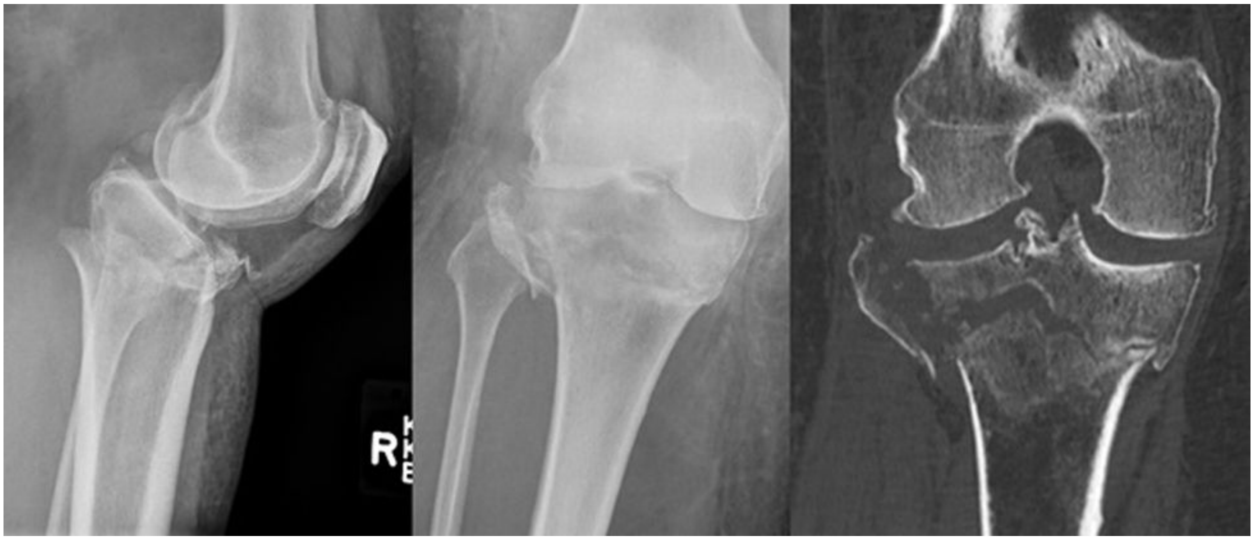

**Figure 4. Example of high clinician ranking but modest fracture energy**

These AP and lateral knee radiographs and a representative coronal CT cut demonstrate osteopenia and substantial metaphyseal impaction without many separate pieces of comminution. The ranking surgeons considered these factors in their assessment of severity, but the fracture energy calculation did not.


**Figure 5. Example of high fracture energy but low surgeon ranking**

These AP and lateral knee radiographs and representative sagittal CT cut demonstrate a fracture that surgeons ranked low in severity due to minimal comminution and depression at the weight bearing portion of the articular surface and very little overall fracture displacement. However, comminution throughout the posterior central portion of the tibial plateau substantially contributed to an increased fracture energy calculation.